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Detecting and measuring new snow accumulation on ice sheets by satellite remote sensing

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Abstract

A new technique is described that detects when and where new snow falls on ice sheets and then determines the thickness of new accumulation. Measurements of vertically polarized passive emission at 85 GHz are filtered with the Hilbert–Huang Transform to identify periods where the surface snow has changed significantly. These are shown to be commonly the result of new snow by comparison with both field observations and in situ instrumentation. Temperature, atmospheric emission and clouds all affect the passive microwave signal but each is examined and shown not to prevent the identification of new snow events. The magnitude of the brightness temperature change is not strongly correlated with snowfall amount. To quantify the amount of new snow, the spatial extent and timing of new snowfalls are examined with ICESat/GLAS laser altimetry data. Crossover differences between altimetric profiles taken before, during, and after the snowfall event provide a measure of the thickness of new snow. Specific cases are presented where 11 and 13 cm of new snow were detected over large regions.

Keywords: Snowfall; Ice sheets; Microwave emission; SSMI; ICESat; Snow event

1. Introduction

Snow accumulates on ice sheets to replenish the mass lost by melting and calving. It is a primary component of the mass balance and, as such, figures heavily into whether an ice sheet changes in volume, affecting sea level, and how it makes these adjustments through altered flow and geometry. It is against the record of past accumulation that present patterns and amounts of accumulation are judged to represent significant changes in either climate or weather.

The majority of the Antarctic Ice Sheet is a high elevation polar desert where a single snowfall may deposit only a thin dusting of new snow. Average net annual accumulation can be as low as 3 cm water equivalent (about 10 cm of snow at a density of 0.3 g/cm^3) (Giovinetto & Zwally, 2000). Indeed, field reports exist from places where no accumulation was received for more than a year and the surface may actually lower through ablation aided by wind scour and densification. Larger snowfalls and annual accumulations are more characteristic of the perimeters of the Antarctic ice sheet and much of its smaller, Greenland sibling.

Despite its importance, the details of snow accumulation on the scale of an ice sheet are poorly known. Great effort has been expended by many people over many years in measuring accumulation amounts in ice cores, snow pits, trenches and with surface stakes or automated acoustic sounders. The universal limitation of these methods is that the data are restricted to a small area and time period. Ice flow introduces an additional complexity because older accumulated snow extracted at depth via an ice core originates upstream from the sample site (except for stable ice domes) and it is well known that surface topographic variations have a strong influence on accumulation (Black & Budd, 1964; Gow & Rowland, 1965; and Whillans, 1975). The pervasiveness of both the spatial and temporal variability

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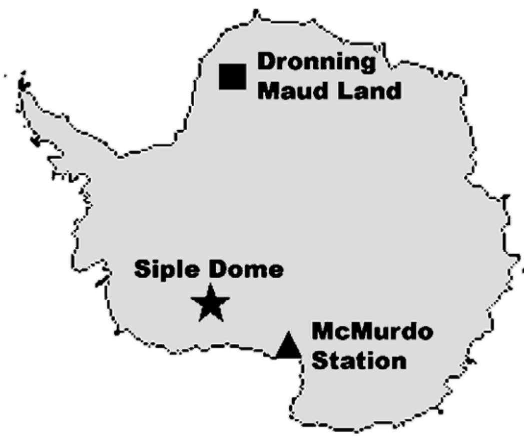

Fig. 1. Location of study areas in Antarctica: Siple Dome (star); McMurdo Station (triangle); and Dronning Maud Land (square).

of ice sheet accumulation has been most recently demonstrated by high-frequency radars towed along the surface that map continuous near-surface layers (Arcone et al., in press; Richardson & Holmlund, 1999). Compilations of accumulation measurements have had to rely on significant interpolations and extrapolations to produce maps of annual accumulation across the vastness of the ice sheets (Bales et al., 2001; Giovinetto & Zwally, 2000; Vaughan et al., 1999). Modeling results can suffer from the same temporal and spatial sampling issues because models frequently use field observations to 'tune' model parameters (Bromwich et al., 2001).

Here we present a new method to identify the extent and timing of new snow on an ice sheet using passive microwave data followed by a quantitative estimate of the amount of new snow across the area by multiple laser altimetric measurements. The technique is based on the observation that the vertically polarized emission at 85 GHz changes when the very top of the snowpack has been altered. By appropriate filtering of these data, we derive a time series that is dominated by the surface signal and is insensitive to unwanted effects caused by passing meteorological systems. These two sensors work independent of solar illumination, so we expect the method to work in all seasons. We make use of direct field observations of weather conditions, including snowfall, and automatic instruments at numerous sites (Fig. 1) to demonstrate the general success of our approach. Once the location and timing of new snow is identified, we use ICESat altimetry data to quantify any change in surface elevation.

2. Identification of snowfall events

2.1. Concept

Our detection approach is designed to identify new snow once it has fallen, not while it is falling. Identification of falling snow particles against a background of snow is expected to be extremely difficult, if not intractable, with current satellite sensors and the temporal frequency of satellite observations might miss entire snowfall events. Our methodology to identify new snow once it had fallen and laid on the surface employs strengths of current sensors, but is not without its own difficulties, as we discuss below.

Our approach employs passive microwave data to detect a difference between old snow that has laid on the surface for some time and new, fresh snow. Snow crystals form in the atmosphere in a variety of shapes, depending on the temperature and pressure conditions during condensation of water vapor onto nucleating surfaces (Nakaya, 1954). Lacy dendrites are most familiar, but other forms, such as platelets, columns or needles, are more commonly formed in the cold, dry conditions above ice sheets. After deposition, they immediately begin to change, diminishing their angularity to form larger, more rounded snow grains. This metamorphic process is ubiquitous and driven by many factors, including temperature, vertical temperature gradients, overlying pressure, humidity, and even wind.

8. Summary

We have demonstrated a new methodology to utilize a combination of remote sensing data to measure the temporal and spatial pattern of new snowfall on ice sheets as well as the thickness of new snow. The vertically polarized brightness temperature at 85 GHz is extremely sensitive to changes caused by the introduction of new, more emissive snow over an aged surface of metamorphosed, more rounded and, therefore, less emissive snow. Over the cold and high-elevation ice sheets the atmospheric contribution due to water vapor, including clouds, is relatively constant at 10 to 13 K and its daily variation is 1 K or less. Temperature changes are more important and directly affect 85 GHz brightness temperatures. Their day-to-day variation is usually only a few Kelvin, less than the observed larger variation in brightness temperature associated with new snow. The Hilbert–Huang Transform (HHT) diminishes many of the undesirable temporal variations of the 85V data and improves the detection of new snow events. Our technique identifies nearly every new snow event observed by field personnel at Siple Dome station in West Antarctica and matches well with acoustic sounder data in Dronning Maud Land. In meteorologically complex regions, such as at McMurdo Station, the ability to detect new snow events is diminished but still significant. Having detected when and where new snow likely occurs, elevation differences at groundtrack crossovers from satellite laser altimeter observations then are used to supply a useful statistical measure of new snow amount.

We believe this work sets out a new direction towards an eventual capability to systematically and comprehensively measure new snow on ice sheets. It is independent of season and, we hope, will eventually lead to routine measurements of new snow and the construction of the climatology of new snow accumulation on ice sheets.